

Tidal Tails around 20 Galactic Globular Clusters

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1 Introduction

In addition to the effects of their internal dynamical evolution, globular clusters suffer strong dynamical evolution from the potential well of their host galaxy (Gnedin & Ostriker 1997, Murali & Weinberg 1997). These external forces speed up the internal dynamical evolution of these stellar systems, accelerating their destruction. Shocks are caused by the tidal field of the galaxy: interactions with the disk, the bulge and, somehow, with the giant molecular clouds, heat up the outer regions of each star clusters. The stars in the halo are stripped by the tidal field. All globular clusters are expected to have already lost an important fraction of their mass, deposited in the form of individual stars in the halo of the Galaxy (see Meylan & Heggie 1997 for a review).

Recent N-body simulations of globular clusters embedded in a realistic galactic potential (Oh & Lin 1992; Johnston et al. 1999) were performed in order to study the amount of mass loss for different kinds of orbits and different kinds of clusters, along with the dynamics and the mass segregation in tidal tails. Grillmair et al. (1995) in an observational analysis of star counts in the outer parts of a few galactic globular clusters found extra-cluster overdensities that they associated partly with stars stripped into the Galaxy field.

We present hereafter our study of the 2-D structures of the tidal tails associated with 20 galactic globular clusters, obtained by using the wavelet transform to detect weak structures at large scale and filter the strong background noise for the low galactic latitude clusters (Leon, Meylan & Combes 1999). We also present N-body simulations of globular clusters in orbits around the Galaxy, in order to study quantitatively and geometrically the tidal effects they encounter (Combes, Leon & Meylan 1999).

2 Observations and Data Reduction

Our sample clusters share different properties or locations in the Galaxy, with various masses and structural parameters. It is of course necessary to have

very wide field imaging observations, consequently, we obtained, during the years 1996 and 1997, photographic films with the ESO Schmidt telescope. The field of view is of $5.5^\circ \times 5.5^\circ$ with a scale of $67.5''/\text{mm}$. The filters used, viz. BG12 and RG630, correspond to B and R , respectively. All these photographic films were digitalized using the MAMA scanning machine of the Observatoire de Paris, which provides a pixel size of $10 \mu\text{m}$. The astrometric performances of the machine are described in Berger et al. (1991).

The next step – identification all point sources in these frames – was performed using SExtractor (Bertin & Arnouts 1996), a software dedicated to the automatic analysis of astronomical images using a multi-threshold algorithm allowing good object deblending. The detection of the stars was done at a $3\text{-}\sigma$ level above the background. This software, which can deal with huge amount of data (up to $60,000 \times 60,000$ pixels) is not suited for very crowded field like the centers of the globular clusters, which were simply ignored. We performed a star/galaxy separation by using the method of star/galaxy magnitude vs. $\log(\text{star/galaxy area})$.

For each field, we constructed a B vs. $(B - V)$ color-magnitude diagram, on which we performed a field/cluster star selection, following the method of Grillmair et al. (1995), since cluster stars and field stars exhibit different colors. In this way we can identify present and past cluster members from the fore- and background field stars by identifying in the CMD the area occupied by cluster stars. The envelope of this area is empirically chosen so as to optimize the ratio of cluster stars to field stars in the relatively sparsely populated outer regions of each cluster.

3 Wavelet Analysis

With the assumption that the data can be viewed as a sum of details with different typical scale lengths, the next step consists of disentangle these details using the space-scale analysis provided by the Wavelet Transform (WT, cf. Slezak et al. 1994; Resnikoff & Wells 1998). Any observational signal includes also some noise, which has a short scale length. Consequently the noise is higher for the small scale wavelet coefficients. We performed Monte-Carlo simulations to estimate the noise at each scale and apply a $3\text{-}\sigma$ threshold on the wavelet coefficients to keep only the reliable structures. In this way it is possible to subtract the short-wavelength noise without removing details from the signal which has longer wavelengths.

The remaining overdensities of the cluster-like stars, remaining after the application of the wavelength transform analysis to the star counts, are associated with the stars evaporated from the clusters because of dynamical relaxation and/or tidal stripping by the galactic gravitational field.

It is worth emphasizing that we have taken into account the following strong observational biases: (i) bias due to the clustering of galactic field

stars; (ii) bias due to the clustering of background galaxies; (iii) bias due to the fluctuations of the dust extinction, as observed in the IRAS 100- μm map.

4 Observational Results

NGC 5139 $\equiv \omega$ Centauri, the most massive galactic globular cluster (Meylan et al. 1995), currently crossing the disk plane, is a nearby globular cluster located at a distance of 5.0 kpc from the sun. Its relative proximity allows to reach the main sequence for the star count selection. We estimate, taking into account the possible presence of mass segregation in its outer parts, that about 0.6 to 1 % of its mass has been lost during the current disk shocking event. Although this cluster has one of our best tail/background S/N ratio, it is by far not the only one exhibiting tidal tails.

Considering all 20 clusters of our sample, we reach the following conclusions (see Leon, Meylan & Combes 1999 for a complete description of this work):

- All the clusters observed, which do not suffer from strong observational biases, present tidal tails, tracing their dynamical evolution in the Galaxy (evaporation, tidal shocking, tidal torquing, and bulge shocking).
- The clusters in the following sub-sample (viz. NGC 104, NGC 288, NGC 2298, NGC 5139, NGC 5904, NGC 6535, and NGC 6809) exhibit tidal extensions resulting from a recent shock, i.e. tails aligned with the tidal field gradient.
- The clusters in another sub-sample (viz. NGC 1261, NGC 1851, NGC 1904, NGC 5694, NGC 5824, NGC 6205, NGC 7492, Pal 5, and Pal 12) present extensions which are only tracing the orbital path of the cluster with various degrees of mass loss.
- NGC 7492 is a striking case because of its very small extension and its high destruction rate driven by the galaxy as computed by Gnedin & Ostriker (1997). Its dynamical “twin” for such an evolution, namely Pal 12, exhibits, on the contrary, a large extension tracing its orbital path, with a possible shock which happened more than 350 Myr.
- The presence of a break in the outer surface density profile is a reliable indicator of some recent gravitational shocks.

Our recent CCD observations with the Wide Field Imager at the ESO/MPI 2.2-m telescope will soon provide improved results, because of the more accurate CCD photometry. These observations will allow more precise observational estimates of the mass loss rates for different regimes of galaxy-driven cluster evolution.

5 Numerical Simulations

We tried with extensive numerical simulations to reproduce the above observations. We performed N-body simulations of globular clusters, in orbits

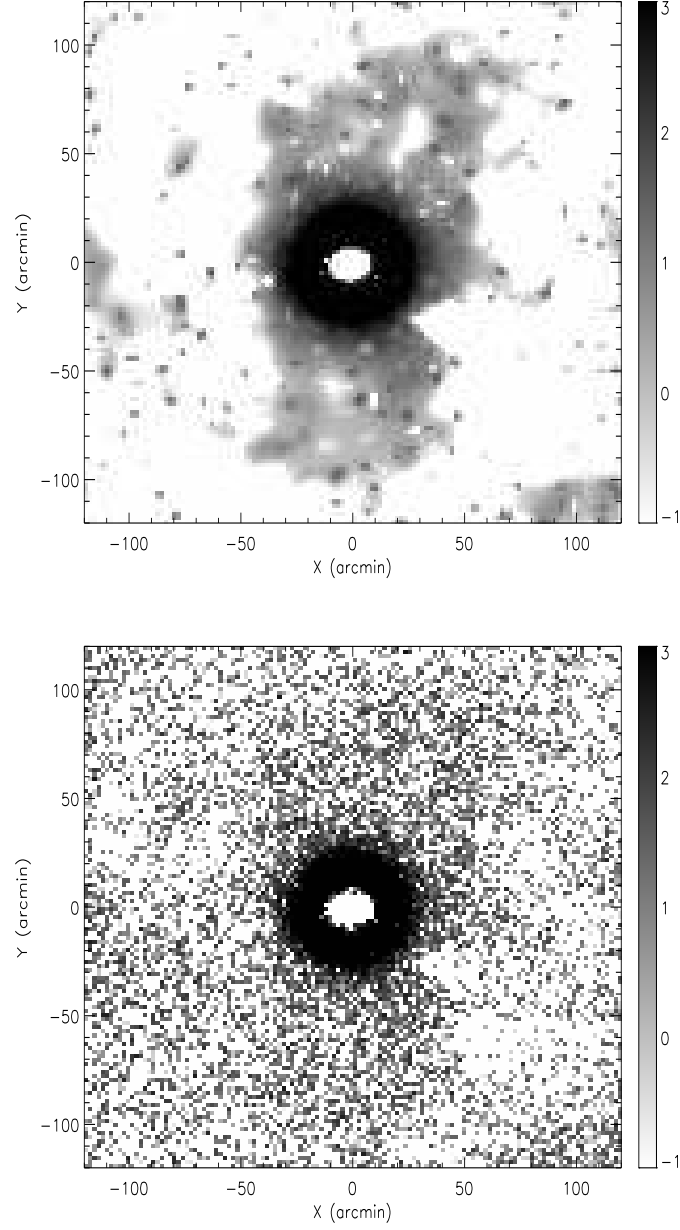


Fig. 1. NGC 5139 $\equiv \omega$ Centauri. In the upper panel, filtered image of color-selected star-count overdensities using the Wavelet Transform to be compared with the raw star counts in the lower panel. The upper panel displays the full resolution using the whole set of wavelet planes.

around the Galaxy, in order to study quantitatively and geometrically the tidal effects they encounter. The N-body code used is an FFT algorithm, using the method of James (1977) to avoid the periodic images. With $N = 150,000$ particles, it required 2.7s of CPU per time step on a Cray-C94.

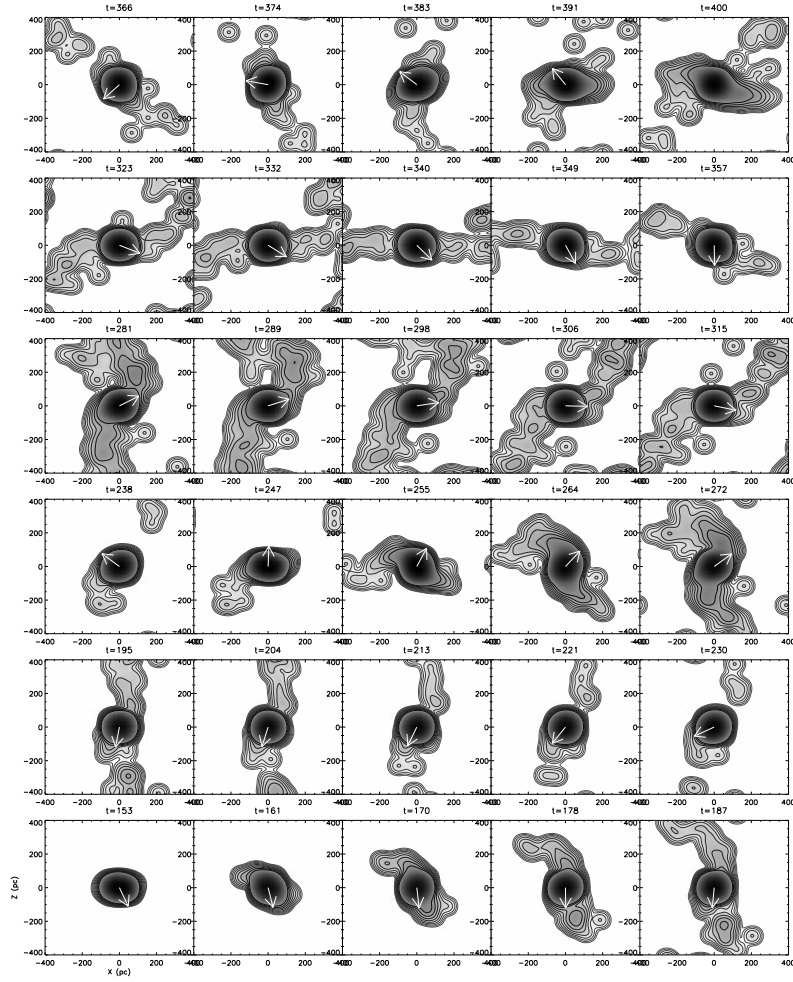


Fig. 2. Tidal tails mapped at different epochs with the wavelet algorithm applied to one of our simulations. The direction perpendicular to the galactic plane is indicated by the arrow. The time sequence starts with the lower-left panel and ends with the upper right one. The third panel exhibit tails which are quite reminiscent of what is observed in NGC 5139 $\equiv \omega$ Centauri (see Fig. 1).

The globular clusters are represented by multi-mass King-Michie models, including mass segregation at initial conditions. The Galaxy is modelled as

realistic as possible, with three components, bulge, disk and dark halo: the bulge is a spherical Plummer law, the disk is a Miyamoto-Nagai model, and the dark matter halo is added to obtain a flat Galactic rotation curve.

The main conclusions of our simulations can be summarized as follows (see Combes, Leon & Meylan 1999 for a complete description of this work):

- All runs show that the clusters are always surrounded by tidal tails and debris. This is also true for those that suffered only a very slight mass loss. These unbound particles distribute in volumic density like a power-law as a function of radius, with a slope around -4 . This slope is much steeper than in the observations where the background-foreground contamination dominates at very large scale.
- These tails are preferentially composed of low mass stars, since they are coming from the external radii of the cluster; due to mass segregation built up by two-body relaxation, the external radii preferentially gather the low mass stars.
- For sufficiently high and rapid mass loss, the cluster takes a prolate shape, whose major axis precess around the z-axis.
- When the tidal tail is very long (high mass loss) it follows the cluster orbit: the observation of the tail geometry is thus a way to deduce cluster orbits. Stars are not distributed homogeneously through the tails, but form clumps, and the densest of them, located symmetrically in the tails, are the tracers of the strongest gravitational shocks.

Finally, these N-body experiments help to understand the recent observations of extended tidal tails around globular clusters (Grillmair et al. 1995, Leon et al. 1999): the systematic observations of the geometry of these tails should bring much information on the orbit, dynamic, and mass loss history of the clusters, and on the Galactic structure as well.

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